**Contract # N00014-14-C-0004**

# Autonomous Control Modes and Optimized Path Guidance for Shipboard Landing in High Sea States

**Progress Report (CDRL A001)**

**Progress Report for Period: January 10, 2015 to April 9, 2015**


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**April 30, 2015**

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**Section I: Project Summary**

## 1. Overview of Project

This project is performed under the Office of Naval Research program on Basic and Applied Research in Sea-Based Aviation (ONR BAA12-SN-0028). This project addresses the Sea Based Aviation (SBA) initiative in Advanced Handling Qualities for Rotorcraft.

Landing a rotorcraft on a moving ship deck and under the influence of the unsteady ship airwake is extremely challenging. In high sea states, gusty conditions, and a degraded visual environment, workload during the landing task begins to approach the limits of a human pilot's capability. It is a similarly demanding task for shipboard launch and recovery of a VTOL UAV. There is a clear need for additional levels of stability and control augmentation and, ultimately, fully autonomous landing (possibly with manual pilot control as a back-up mode for piloted flight). There is also a clear need for advanced flight controls to expand the operational conditions in which safe landings for both manned and unmanned rotorcraft can be performed. For piloted rotorcraft, the current piloting strategies do not even make use of the available couplers and autopilot systems during landing operations. One of the reasons is that, as the deck pitches and rolls in high sea states, the pilot must maneuver aggressively to perform a station-keeping task over the landing spot. The required maneuvering can easily saturate an autopilot that uses a rate limited trim system. For fly-by-wire aircraft, there is evidence that the pilot would simply over-compensate and negate the effectiveness of a translation rate command/position hold control mode. In addition, the pilots can easily over-torque the rotorcraft, especially if they attempt to match the vertical motion of the deck.

This project seeks to develop advanced control law frameworks and design methodologies to provide autonomous landing (or, alternatively, a high level of control augmentation for pilot-in-the-loop landings). The design framework will focus on some of the most critical components of autonomous landing control laws with the objective of improving safety and expanding the operational capability of manned and unmanned rotorcraft. The key components include approach path planning that allows for a maneuvering ship, high performance station-keeping and gust rejection over a landing deck in high winds/sea states, and deck motion feedback algorithms to allow for improved tracking of the desired landing position and timing of final descent.

## 2. Activities this period

*Task 1 - Plant and Disturbance Model*

One of the important aspects of this project is to have high fidelity dynamic models of the rotorcraft and accurate simulation of the shipboard environment. A generic medium class helicopter model has been developed using FLIGHTLAB modeling and simulation software, and the preliminary version of this model was provided for supporting the control system design and simulation testing. During this reporting period, the medium class helicopter model has been updated to include both ship motion dynamics and ship airwake model. The ship model was developed using the publically available information of a generic DDG class ship. The prescribed sinusoidal functions were used to represent the ship's motion. The frequencies, phases, and amplitude of the sinusoidal functions were extracted using FLIGHTLAB's 6 DOF ship modeling utility to provide reasonable ship motions of a generic DDG class ship. In addition, a set of CFD ship airwake data from PSU was processed and integrated with the generic medium weight class helicopter to simulate the effects of nonuniform and turbulent ship airwake on the rotorcraft model. In future activities, this airwake data will be expanded to cover more WOD conditions.

At the same time, a generic light weight helicopter (FireScout class) has also been developed using the

FLIGHTLAB. The generic light weight class helicopter model includes high fidelity models of the coupled non-linear fuselage and rotor blade dynamics, unsteady rotor aerodynamics and induced inflow dynamics, non-linear landing gear, ideal engine model, blade element tail rotor modeling, simple flight control system with SAS, and the capability to simulate unsteady ship airwake and ship motion effects. Once its reasonability test is done, the model will be ready for integration with the shipboard landing control laws.

*Task 2 – Overall Control Architecture*

A new PhD student started on the project at Penn State in January 2015, Junfeng Yang. During his initial training period he has gained familiarity with the dynamic inversion control architecture and with the software environment. He is now fully trained in running simulation cases and making control law modifications. He is currently running simulation cases in support of the path optimization work led by John Tritschler as discussed below.

*Task 4 – Dynamic Inversion Control Design*

The inner loop dynamic inversion controller from PSU was been integrated into the medium class helicopter FLIGHTLAB model during last reporting period. During this reporting period Penn State completed implementation of the outer loop control design in CSGE and FLIGHTLAB. We have also demonstrated closed loop control of approach trajectories to a moving landing deck. In addition to the outer loop guidance, the controller includes a trajectory generation element, to automate the approach and smoothly transition to station-keeping over the deck. This is somewhat different form previous controller designs tested with the GENHEL model, which used pre-computed trajectories calculated off-line and stored in look up tables. The trajectory parameterization is now computed directly in the CSGE control block diagrams. As proposed in previous work by Tritschler et al, the approach trajectory is parameterized by the range to the landing spot, and the decelerating decent is based on approach profiles observed for human rotorcraft pilots, [1] and [2]. Approach speed is defined by the relationship:

$$V_{app} = \frac{\left(\dfrac{v_0}{2r_{pd}}\right) r}{\left(1 + \dfrac{r}{2r_{pd}}\right)} \tag{1}$$

where $r$ is the range. The tunable constants $r_{pd}$ and $v_0$ represent the range to peak deceleration and asymptotic approach velocity, respectively. The approach path follows a constant glide slope, $\gamma$, and a relative azimuth, $\psi$, such that the forward, lateral, and vertical velocity of the helicopter in the ship frame are given by:

$$\Delta\dot{x} = -V_{app}\cos\gamma\cos\psi \quad \Delta\dot{y} = -V_{app}\cos\gamma\sin\psi \quad \Delta\dot{h} = V_{app}\sin\gamma \tag{2}$$

These provide ship relative coordinates, which are then converted to inertial coordinates and inertial velocities that are tracked by the outer loop control law.

In the sample simulations presented below, the helicopter approaches a ship moving at 20 knots with a heaving deck ±8 ft amplitude and a 12 second period. The approach is directly from the stern and there is no airwake in this simulation. Figures 1-2 show a sample trajectory as the helicopter starts 3000 ft aft of the ship, 230 ft altitude, and 79 knots airspeed. The decelerating approach is performed along an 8 degree glide slope. As the range is reduced the helicopter begins to match the vertical heave motion of the ship. A blending algorithm is used to smoothly transition from a commanded inertial altitude profile to a ship relative altitude over the deck.

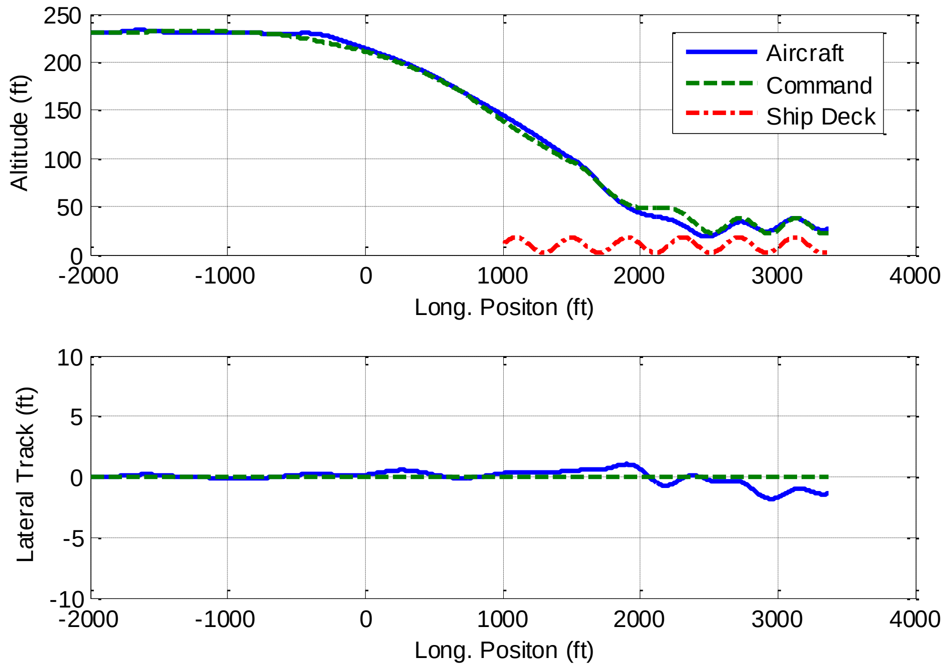


Figure 1 Trajectory of Sample Approach

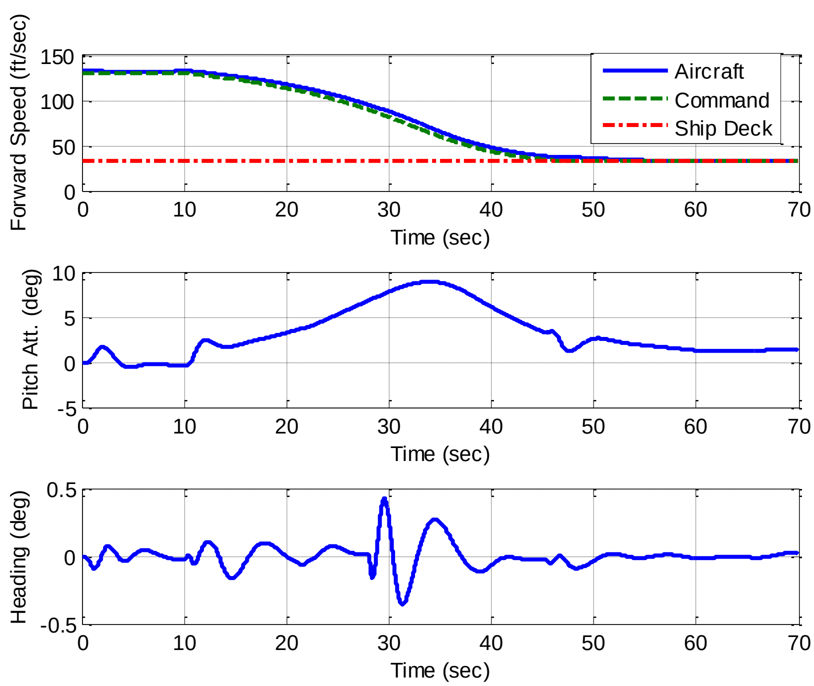


Figure 2 Time History of Sample Approach

The results above were generated with no airwake and a prescribed sinusoidal motion of the ship. As discussed under Task 1, the FLIGHTLAB models were updated to include representative ship motion and airwake turbulence. In addition, the model now provides measured ship motion data into the CSGE control laws for use in ship relative control. We have run multiple approach simulations with airwake, ship motion, and moving ground effect influence on the main rotor. We will present more comprehensive results in the next progress

report.

*Task 5 – Deck Motion Prediction Algorithm*

The efforts during the previous reporting period were made to implement a minor component analysis (MCA) based dynamic forecasting method. The minor component is the direction in which the data has the smallest covariance. The MCA determines the directions of smallest variance in a distribution. They correspond to the directions of those eigenvectors of the covariance matrix of the data which have the smallest eigenvalues. The proposed MCA based ship motion forecasting algorithm was implemented and tested for a set of simulation data of a full 6-DOF ship motion using USN SMP and STH. In order to provide quantified performance criteria, several statistical terms, such as mean value and standard deviation, were used. From the initial testing, the MCA forecasting algorithm predicted the ship motion reasonably well for wave heading angles between ±45 degrees and sea state 3 condition with reasonable forecasting time.

During this reporting period, efforts were made to enhance the MCA based forecasting method. There are several variables which have important role in the MCA algorithm. For example, number of windows, window size, number of data blocks, and correction factors should be properly defined to give a good forecasting performance. In general, the more data are used in the MCA the better prediction of ship motion. However, it is not efficient to process thousands of data to perform the eigen-analysis for a real-time simulation process. Thus a set of design variables was defined and prepared for the integration into the FLIGHTLAB.

*Task 6 - Path optimization of shipboard helicopter:*

Investigation of path optimization methods has continued during this reporting period. In the previous progress report, the development of various objective functions was presented and a simple sensitivity analysis was conducted. This initial work was conducted using the GENHEL based simulations. Since that time, we have transitioned to using the FLIGHTLAB simulations for the path optimization studies. The baseline trajectories were re-generated in FLIGHTLAB, and the objective functions were re-evaluated. We then iterated on numerous variations in the approach trajectories based on the resulting objective functions and their sensitivities. The results of this study will be presented in an AIAA paper, which is due in late May 2015. We will also present details of this analysis in the next progress report.

## 3. Significance of Results

The medium weight class helicopter model was enhanced that includes the effects of generic ship motion using prescribed summation of sinusoidal motion with multiple frequencies and random phases, turbulent ship airwake, and DI controller. A light weight class helicopter model has been developed to using FLIGHTLAB. The deck motion forecast method based on the MCA algorithm was enhanced for integration into FLIGHTLAB simulation environment.

The complete DI control architecture has been implemented in CSGE and FLIGHTLAB, including on-line path generation using the parameterization scheme presented in [1] and [2]. The controller has been tested and provided to our collaborators at the U.S. Navy. This closed-loop simulation is now currently supporting the path optimization studies.

## 4. Plans and upcoming events for next reporting period

*Task 1 – Plant Model and Disturbance Models*: The development of FireScout and heavy weight (H-53 class) FLIGHTLAB flight dynamics models will be accomplished.

*Task 4 –* We will investigate required vertical, lateral, and longitudinal axis bandwidth required to track typical deck motions in high sea state. In addition, we will investigate integration of ship motion prediction into the control laws to understand their potential benefit in minimize relative deck motion in landing.

*Task 5 – Ship Motion Prediction*: Next effort will be focused on the integration of MCA method into FLIGHTLAB software.

*Task 6 - Path optimization of shipboard helicopter:* We will continue path optimization study, culminating in the AIAA paper in June 2015. Running the ship approaches for the optimization study also provides comprehensive testing of the NLDI control laws, and helps identify issues or areas of improvement in support of Task 5.

## 5. References


1. Heffley, R. K., "A Model for Manual Decelerating Approaches to Hover," 15th Annual Conference on Manual Control Proceedings, Air Force Flight Dynamics Laboratory, Dayton, OH, November 1979, pp. 545–554.
2. Tritschler, J. K., Celi, R., and Leishman, J. G., "Methodology for Rotorcraft Brownout Mitigation Through Flight Path Optimization," Journal of Guidance, Control, and Dynamics, Vol. 37, No. 5, September–October 2014, pp. 1524–1538.


## 6. Transitions/Impact

The DI Controller with automated ship approach path following was transitioned to our counterparts at NAVAIR and NSWCCD (Sean Roark and Al Schwarz), and to John Tritschler (now at USNTPS). The simulation with the DI control law was successfully run at NSWCDD (in fact during the transition process, Al Schwarz was able to identify a bug in the FLIGHTLAB model which was subsequently fixed). We continue to provide updates to the models and control laws to our counterparts at the U.S. Navy.

## 7. Collaborations

Penn State and ART have collaborated directly with John Tritschler and Sean Roark at NAVAIR. In addition, we are communicating with other Navy researchers pursuing similar projects: Al Schwarz at NSWCCD who is investigating ship motion prediction and AutoLand, and Dave Findlay at NAVAIR who is investigating advanced control laws for shipboard landing. We have transferred the current version of the DI control laws (in FLIGHTLAB CSGE format) to Al Schwarz and Sean Roark. We will be meeting and coordinating with Dave Findlay, Colin Wilkinson, and Eric O'Neill at NAVAIR in late May.

## 8. Personnel supported

Principal investigator: Joseph F. Horn

Graduate Students: Junfeng Yang, PhD Candidate

## 9. Publications

A draft manuscript was accepted to the 2015 AIAA AFM Conference at AVIATION 2015: Tritschler J.K. and Horn J.F. “Objective Function Development for Optimized Path Guidance for Rotorcraft Shipboard Recovery”. The paper will be presented in Dallas TX, June 22-26 2015

An abstract was an accepted to the 2015 European Rotorcraft Forum in Munich Germany, September 1-3, 2015: Horn J.F., He, C., and Lee, D. “Autonomous Ship Approach and Landing using a Dynamic Inversion Control with Deck Motion Prediction.”

## 10. Point of Contact in Navy

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## 11. Acknowledgement/Disclaimer

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**Section II: Project Metrics**

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**April 30, 2015**

## 1. Metrics

Number of faculty supported under this project during this reporting period: 1

Number of post-doctoral researchers supported under this project during this period: 0

Number of graduate students supported under this project during this reporting period: 1

Number of undergraduate students supported under this project during this period: 0

Number of refereed publications during this reporting period for which at least 1/3 of the work was done under this effort: 0

Number of publications (all) during this reporting period: 0

Number of patents during this reporting period: 0

Number of M.S. students graduated during this reporting period: 0

Number of Ph.D. students graduated during this reporting period: 0

Awards received during this reporting period: 0

Invited talks given: 0

Conferences at which presentations were given (not including invited talks above): 0